NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2152

SHEAR STRESS DISTRIBUTION ALONG GLUE LINE BETWEEN SKIN AND CAP-STRIP OF AN AIRCRAFT WING

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Forest Products Laboratory

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SUMMARY

In aircraft wing construction, the stress distribution along the glue line between a cap-strip and the skin where forces are transferred from the skin to the cap-strip by means of shear stresses is not uniform, but is affected by a stress raiser at the re-entrant corner between the cap-strip and the skin.

Thousands of strain determinations along the glue line of 50 laminated specimens made of wood show that the stresses increase rapidly from zero at the re-entrant corner to a maximum at a very short distance from the edge, then gradually diminish throughout the rest of the length to a short distance from the other edge, and then rapidly drop to zero. The maximum shear stress concentration found in the tests is about 50 percent greater than the average shear stress.

The stress concentrations are plotted to parameters suggested by the work of other investigators and a curve from which values of stress concentration can be estimated is obtained.

INTRODUCTION

In the manufacture of aircraft, the outside skin of the craft is fastened to the cap-strips of the ribs and spars of the framework. This fastening is sometimes made by means of an adhesive. Forces in the skin are transmitted to the spars or ribs by means of shear stress in the adhesive. These forces occur in the plane of the skin and may be directed at right angles to the length of the spars or ribs. The area of the fastening and the strength of the adhesive should be sufficient to transmit the forces safely to the ribs or spars.

The skin and the cap-strips of the spars or ribs are deformed by the forces and, therefore, the shear stress is not uniformly distributed across the fastening but is concentrated in the neighborhood of its edges.

It is the purpose of this report to estimate the amount of these concentrations so that such fastenings may be more safely and economically designed.

A conventionalized symmetrical specimen made of wood was used in the work. (See fig. 1.) The outer two laminations simulate skins and are fastened to the adjacent laminations by means of an adhesive. The adjacent laminations simulate cap-strips and are fastened to the central lamination which in turn simulates the rib or spar. The grain direction of the wood of the outer and central laminations is in the direction of the load and the grain direction of the intermediate laminations is at right angles to the plane of the face of the specimen. Thus the specimen represents a cross section of two cap-strips and two skins. The symmetry of the specimen causes the central ply, simulating the rib or spar, to act as if it were infinitely rigid in bending. The applied load induces shear stresses in the cap-strips or intermediate laminations, compression in the skins or outer laminations and in the rib or central lamination, and some bending in the cap-strips and skins.

The shear stress distribution in a similar specimen was determined photoelastically in reference 1 and mathematically, approximately but quite accurately, in reference 2. In the former determination the outer and central laminations were exceedingly rigid with respect to the intermediate lamination; in the latter the two boundaries of the sheared plate were assumed infinitely rigid. Thus the results obtained are not directly applicable to the present investigation.

Investigations of a similar problem have been made in connection with the determination of the strength of glued joints. (See references 3 and 4.) These investigations take into account the compressive strains in the outer and central laminations. The former also takes into account the bending stresses in these laminations but the latter considers them infinitely rigid in bending. They both consider the distribution of shear stress across the thickness of the intermediate laminations to be uniform and, therefore, they also are not directly applicable to the present investigation.

The present work involves the experimental determination of the distribution of shear stress in a plane parallel to and a short distance from the fastening between the outer and intermediate laminations and of the effect upon this distribution of changing the length and width of the specimen. Parameters taken from the previous investigations referred to are used in plotting the values of stress concentration obtained. It is assumed that the shear stresses are proportional to the shear strains, the strains being measured in the tests.

This investigation was conducted under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

TEST SPECIMENS

The test specimens, seven in number, were made of Sitka spruce lumber which was chosen particularly for straightness of grain and uniformity of growth rings. To approximate roughly the conditions encountered in the combination of skin and cap-strip, a glued-up symmetrical specimen was used. This specimen, shown in figure 1, was composed of five laminations glued together: Two edge-grain outer laminations which simulated the skin, two end-grain intermediate laminations which simulated the cap-strip, and an edge-grain center lamination to simulate the aircraft wing rib. After each series of tests the specimen was cut to a shorter length and another series of tests made. This process was repeated until the ratio of width to thickness of the cap-strip became $2\frac{2}{3}$.

The dimensions of the various laminations for each test were always such that the thickness of the central lamination was twice the thickness of the individual outer laminations, and the length of these laminations was such that a line drawn from the center of the loaded end of the center lamination to the center of the reaction end of either one of the outer laminations passed through the diagonally opposite corners of the intermediate lamination. The intermediate laminations were originally 6 inches long (corresponding to a cap-strip width of 6 in.) and 3/4 inch thick but were shortened as previously indicated. Three thicknesses of outer laminations, 3/4, 3/8, and 3/16 inch, were used. All laminations, and consequently the specimen, were 1 inch wide.

TEST APPARATUS

The test apparatus (fig. 1) included a 6- by 6-inch steel plate 1 inch thick which had a V-groove machined diagonally across the upper face. In this groove were placed two 1/4-inch-diameter steel balls. On top of each ball a 1-inch-square steel plate 1/4 inch thick was centered. The ends of the outer laminations were centered on these smaller plates. These smaller plates had punch marks at their centers to facilitate centering on the balls and marked center lines on their edges to assist in centering the specimen. Two similar small plates with a similarly centered ball between them were also centered on top of the central lamination. A roller assembly permitting lateral movement in a direction parallel to the face of the specimen between the upper plate and the loading head of the testing machine completed the test apparatus.

Strain determinations were made by means of Tuckerman strain gages.

METHOD OF TEST

The specimens were brought to equilibrium moisture content in a conditioning room at 64-percent relative humidity and at a temperature of 75° F. After this they were finished to the final dimensions.

A line was drawn on one of the intermediate laminations 1/8 inch from, and parallel to, the glue line between this and the outer lamination. This line was divided into segments 1/4 inch long. Through the end of each segment two mutually perpendicular lines were drawn at an angle of 45° to the glue line. These diagonal lines facilitated the mounting of Tuckerman strain gages during the test.

The specimens were centered in the test apparatus previously described. Once the specimen was centered and plumbed, it was held in the testing machine by maintaining a load of at least 20 pounds at all times until all strain determinations for that length of specimen had been completed.

A Tuckerman strain gage having a gage length of 1/4 inch was mounted on one of the 45° lines drawn as previously described, centered on the end of the corresponding line segment, and held in place by means of a C-clamp which reached around the specimen. The strain gage was read, the load on the specimen increased to that equivalent to an average shear stress of 20 psi in the intermediate laminations, and the strain gage read again. This process was repeated for each of the 45° lines drawn on the specimen. This tedious process was necessary because it was desired to obtain readings at points spaced so closely that adjacent gages could not be used. Metalelectric strain gages of 1/4-inch gage length were tried, but satisfactory readings were not obtained. After the readings for the 45° lines on the specimen were obtained, the specimen was removed from the test apparatus and its length reduced. A length of 1 inch was cut off the shoulders of the specimen and the lengths of the outer and central laminations were reduced to the dimensions previously described. After this reduction in lengths another series of tests was made. This process was repeated until the width of the cap-strip was reduced to 2 inches. The tests were conducted in the conditioning room in which the specimens had been brought to equilibrium moisture content.

During the tests of most specimens, strain determinations were made on only one face of one of the intermediate laminations at a time. In tests on specimens 9A and 10A, strain determinations on both faces of one of the intermediate laminations were made simultaneously by using two strain gages, and average values of the strains obtained were tabulated. The tests required the determination of several thousands of strains.

RESULTS

Table 1 contains the shear stress concentrations for all the specimens. The second column lists the specimen number; the third column denotes from which edge and cap-strip the strain measurements were obtained, as viewed by the observer. The last five columns list the percentage shear stress concentrations obtained for the various ratios of width of cap-strip to thickness of cap-strip. These values are obtained by subtracting the average of all shear strain readings for a particular width of cap-strip from the maximum reading for that length and dividing by the average value. Three sets of results are presented for the three ratios of thickness of skin to thickness of cap-strip.

Figures 1 and 2 show the test apparatus and method of attaching the Tuckerman optical strain gages.

Figure 3 shows the diagrams of shear strain distribution for the successive tests of the various specimens. The broken line indicates the average value of the plotted strains. The values plotted are the shear strains associated with two planes perpendicular to the face of the specimen and parallel and perpendicular, respectively, to the plane of the joint between the outer and intermediate laminations. These values were calculated by subtracting one of the strains from the other obtained at the same point on the cap-strip.

Figure 4 is a family of curves showing the effect of variations in the width of the cap-strip on the percentage shear stress concentration for the various ratios of thickness of skin to thickness of cap-strip. These curves are drawn to cover only the range of the data obtained.

Figure 5 is a plot of the same data to the parameter

$$L\sqrt{\frac{G}{Ewt}}$$

suggested by references 3 and 4. In this parameter:

L length of intermediate laminations; width of cap-strip

w thickness of intermediate laminations; thickness of cap-strip

t thickness of outer laminations; thickness of skin

G modulus of rigidity of intermediate laminations

E modulus of elasticity of outer laminations

DISCUSSION

Two strains were measured at each of the various points located on the cross section of the cap-strip. The directions of the two strains were mutually perpendicular and inclined at an angle of 45° to the joint between the cap-strip and skin. Thus the shear strains in the plane of the cross section of the cap-strip and associated with axes perpendicular and parallel to the glue line can be computed. The transformation equations for shear strains e associated with the axes ξ and η in terms of the axes x and y rotated from the former through an angle θ (taken from reference 5) are:

$$e_{\xi\xi} = e_{xx} \cos^2\theta + e_{yy} \sin^2\theta + e_{xy} \sin\theta \cos\theta$$

$$e_{\eta\eta} = e_{xx} \sin^2\theta + e_{yy} \cos^2\theta - e_{xy} \sin\theta \cos\theta$$

(The third equation given in reference 5 will not be required.) Thus, if $\theta = 45^\circ$,

$$e_{\xi\xi} = \frac{1}{2} e_{xx} + \frac{1}{2} e_{yy} + \frac{1}{2} e_{xy}$$

$$e_{\eta\eta} = \frac{1}{2} e_{xx} + \frac{1}{2} e_{yy} - \frac{1}{2} e_{xy}$$

and

$$e_{\xi\xi} - e_{\eta\eta} = e_{xy}$$

Thus the shear strain required is merely the difference of the two direct strains measured.

Shear strains computed in this way are plotted in figure 3 against distances across the width L of the cap-strip. The strains at the edges of the cap-strip are, of course, zero. The strain distribution is not symmetrical about the center of the cap-strip. The highest strain occurs near the re-entrant corner between the skin and the cap-strip and decreases across the width of the cap-strip. This distribution is probably caused by the re-entrant corner and by the difference in stiffness in bending between the central and outer laminations of the specimen.

The central lamination probably acts as if it were infinitely rigid in bending because of the symmetry of the specimen. For some of the shorter specimens the maximum strain occurs near the center of the cap-strip as indicated in references 1 and 2.

The strain concentrations (table 1) were found for each specimen by subtracting the average strain from the maximum strain and dividing by the former. The averages of the values obtained in this way are plotted against the ratio of the width to the thickness of the cap-strip in figure 4. Three groups of points are obtained, one for each of the three ratios of thickness of skin to thickness of cap-strip for which tests were made. These points roughly follow the three straight lines drawn in the figure.

The strain concentration seems to decrease as the ratio of the width to thickness of the cap-strip decreases, but not so rapidly as might be expected from references 3 and 4, which indicate no strain concentration when the length of the joint is small. However, references 1 and 2 indicate strain concentrations near the edges of the cap-strip for wide cap-strips, a single concentration at the center of the cap-strip if the cap-strip is sufficiently narrow, and a minimum value of concentration when the width of the cap-strip is about twice its thickness. Unfortunately it was not practical to carry the tests into this range. References 3 and 4 indicate that the curves in figure 4 approach straight lines having positive slopes for very wide cap-strips.

The work in references 3 and 4 suggests the parameter:

$$L\sqrt{\frac{G}{Ewt}}$$

in which

L width of cap-strip

w thickness of cap-strip

t thickness of skin

G modulus of rigidity of cap-strip

E modulus of elasticity of skin

and the former suggests also the parameter t/w because of the bending of the specimen. The strain concentrations obtained from the tests are plotted to these parameters in figure 5. The ratio G/E has a value of about 0.0038 for the spruce used in making the specimens. Figure 5 shows that the effect of the parameter t/w can be neglected unless the thickness of the skin is about equal to or greater than that of the cap-strip and that its effect, then, is to reduce the value of the stress concentration. This figure makes it possible to estimate the strain concentrations in materials other than that of the specimens tested.

It should be mentioned that concentrations of direct strain occur at the edges of the cap-strip. Investigation of this concentration was not included in this work.

CONCLUDING REMARKS

Thousands of strains determined along the glue line of 50 laminated specimens made of wood show that the stresses increase rapidly from zero at the re-entrant corner to a maximum at a very short distance from the edge, then gradually diminish throughout the rest of the length to a short distance from the other edge, and then rapidly drop to zero. The maximum shear stress concentration found in the tests is about 50 percent greater than the average shear stress.

Forest Products Laboratory
Madison, Wis., January 18, 1949

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TABLE 1.- EFFECT OF VARIOUS RATIOS OF SKIN AND CAP-STRIP

DIMENSIONS ON SHEAR STRESS CONCENTRATION

t/w (1)	Specimen	Edge (2)	Shear stress concentration (percent) for - L/w = 8 (3)	L/w = $6\frac{2}{3}$ (3)	L/w = $5\frac{1}{3}$ (3)	L/w = 4 (3)	L/w = $2\frac{2}{3}$ (3)
1/4	6A	Right	38.39	43.41	34.24	33.75	24.79
1/4		Left	50.82	43.85	38.93	34.55	33.97
1/4	10A	Right	56.48	38.31	37.93	43.85	32.31
1/4		Left	57.22	58.24	60.08	41.32	41.38
1/4	Average		50.73	45.95	42.80	38.37	33.11
1/2	6A	Right	37.61	-----	-----	-----	25.9
1/2	3A	Right	32.91	30.71	29.39	26.41	23.55
1/2	8A	Right	52.74	57.22	54.58	37.68	40.74
1/2		Left	49.72	38.96	36.83	30.54	34.97
1/2	Average		43.25	42.30	40.27	31.54	31.29
1	4A	Right	40.74	29.06	25.38	21.96	22.32
1	9A	Right	26.68	29.50	30.04	28.29	31.41
1		Left	24.98	27.75	25.51	30.40	24.45
1	Average		30.8	28.77	26.98	26.88	26.06

[1]t, thickness of skin; w, thickness of cap-strip.

[2]Right means right edge of right cap-strip; left means left edge of left cap-strip.

[3]L, width of cap-strip; w, thickness of cap-strip.

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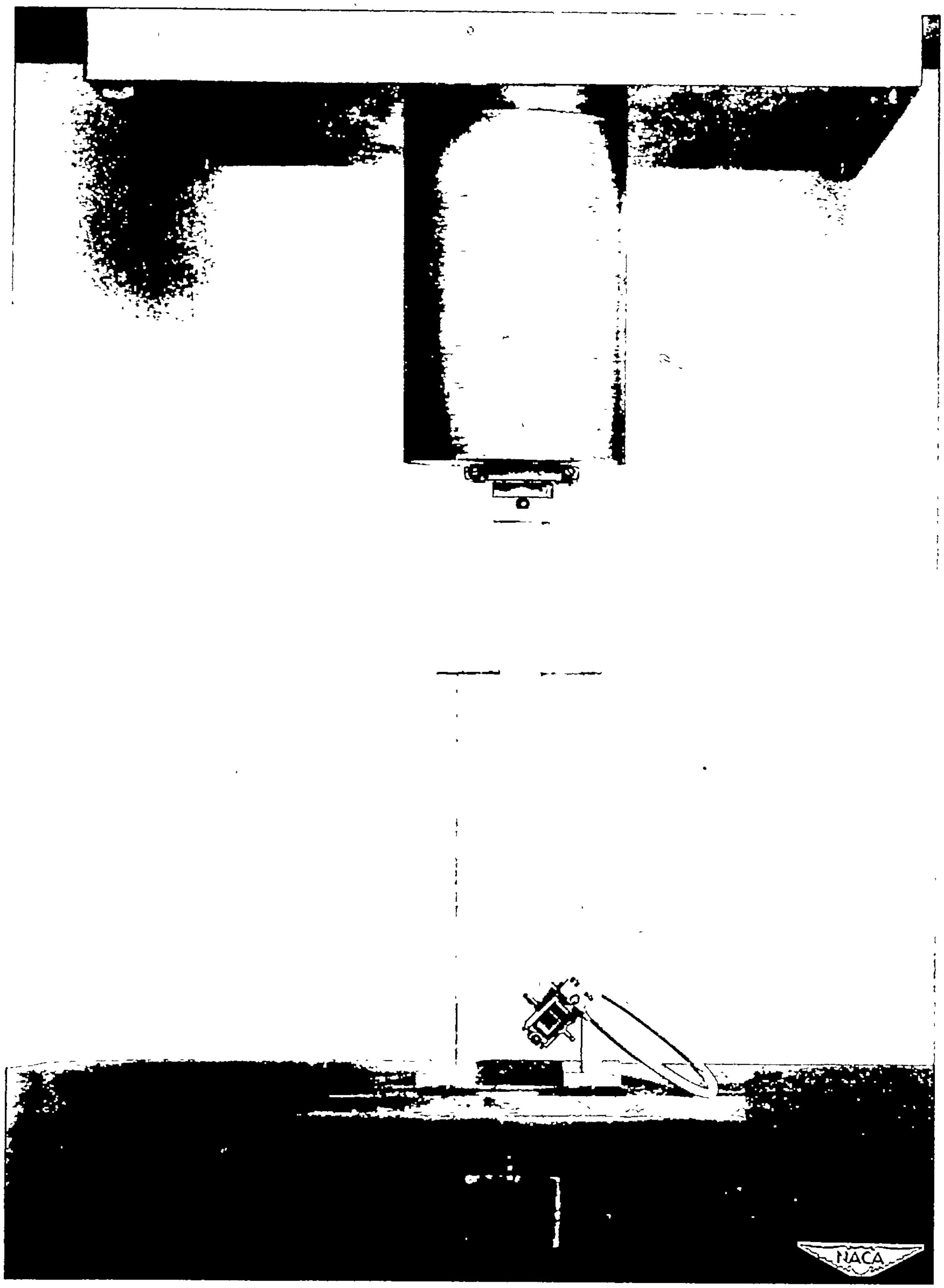
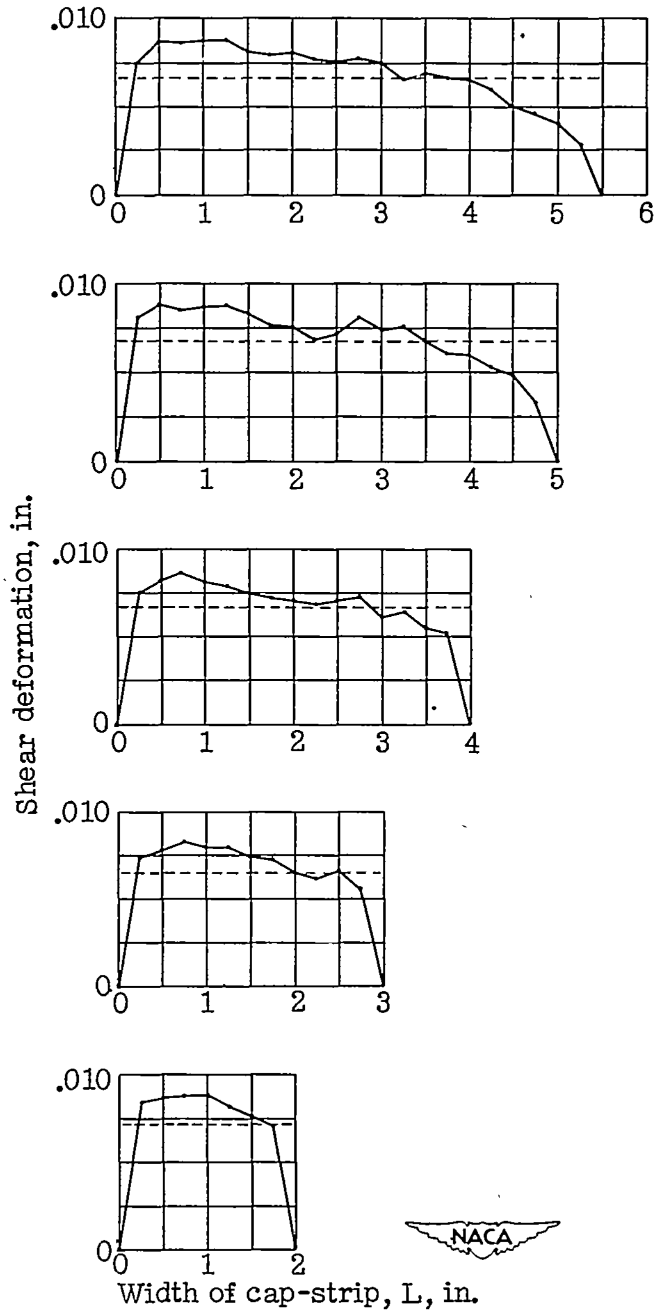


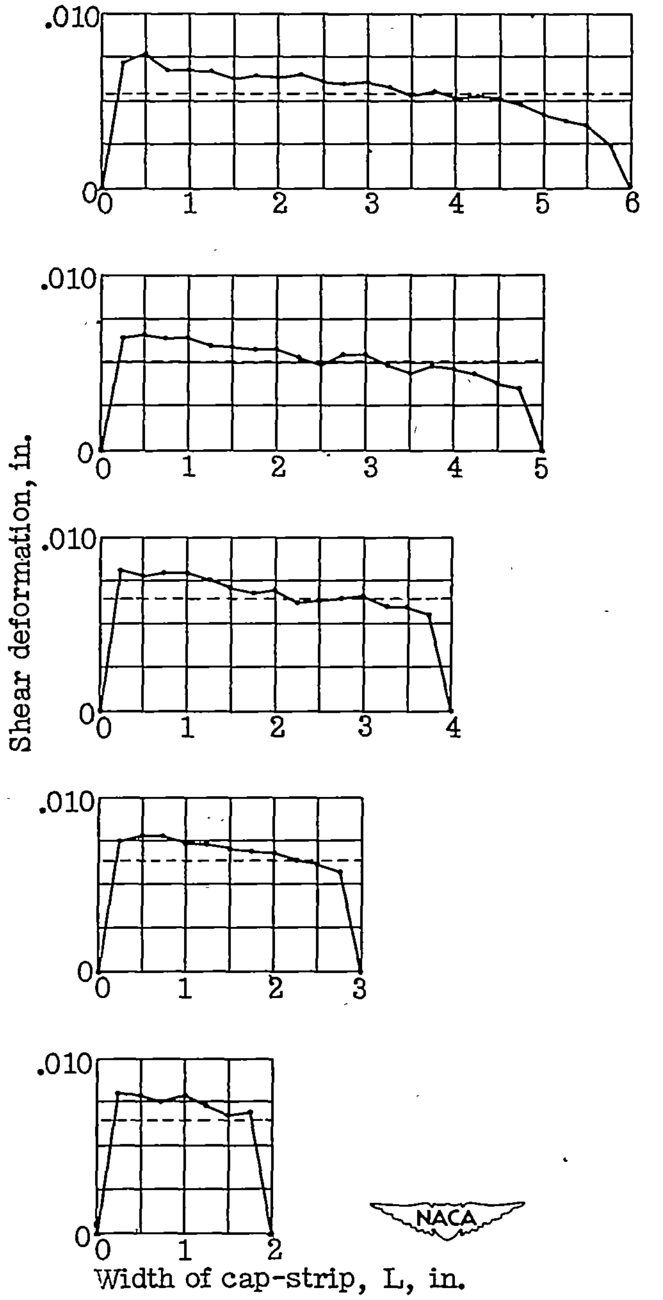
Figure 1.- Test apparatus and full-length specimen ready for testing in machine.

Figure 2.- Same test setup as shown in figure 1 with specimen reduced to final dimensions.



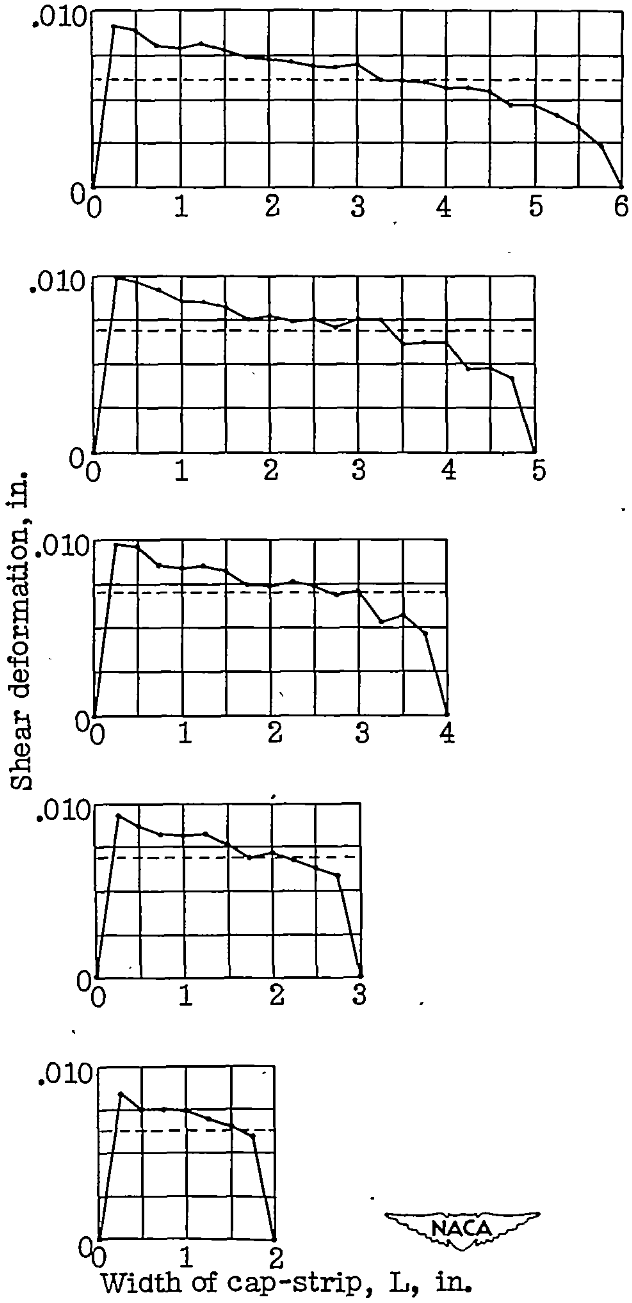
(a) Specimen 3A, right edge.

Figure 3.- Shear strain distribution for cap-strip. Broken line indicates average value of plotted strains.



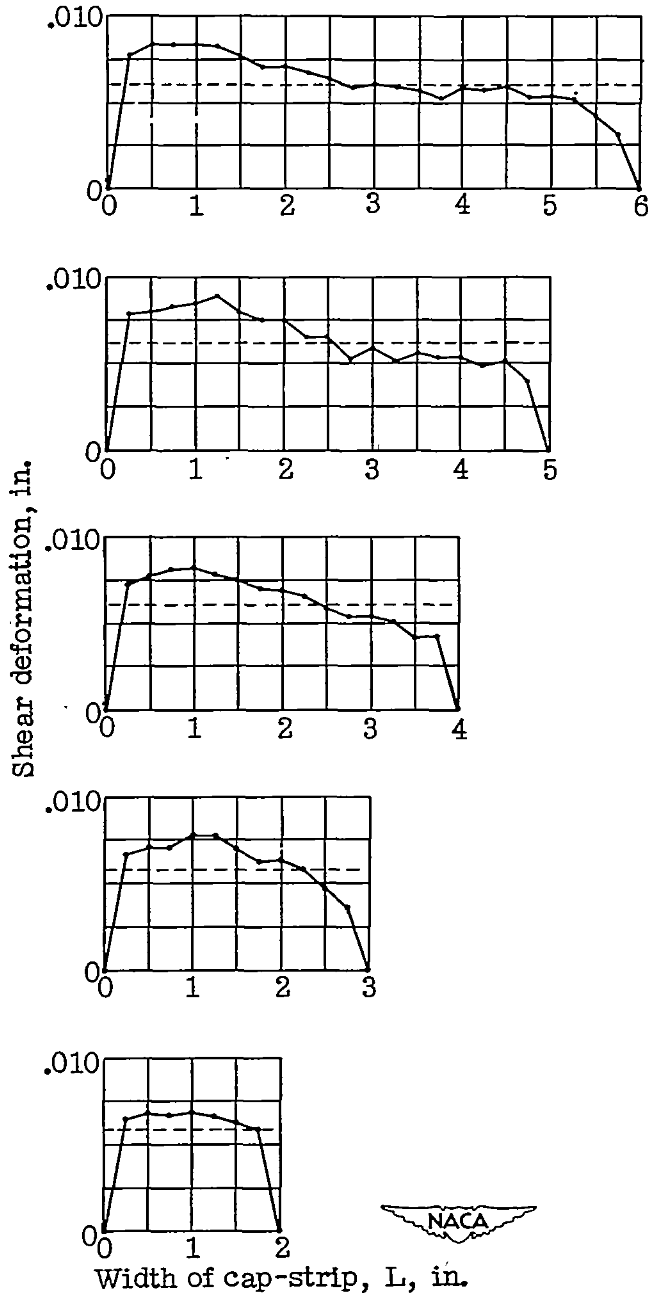
(b) Specimen 4A, right edge.

Figure 3.- Continued.



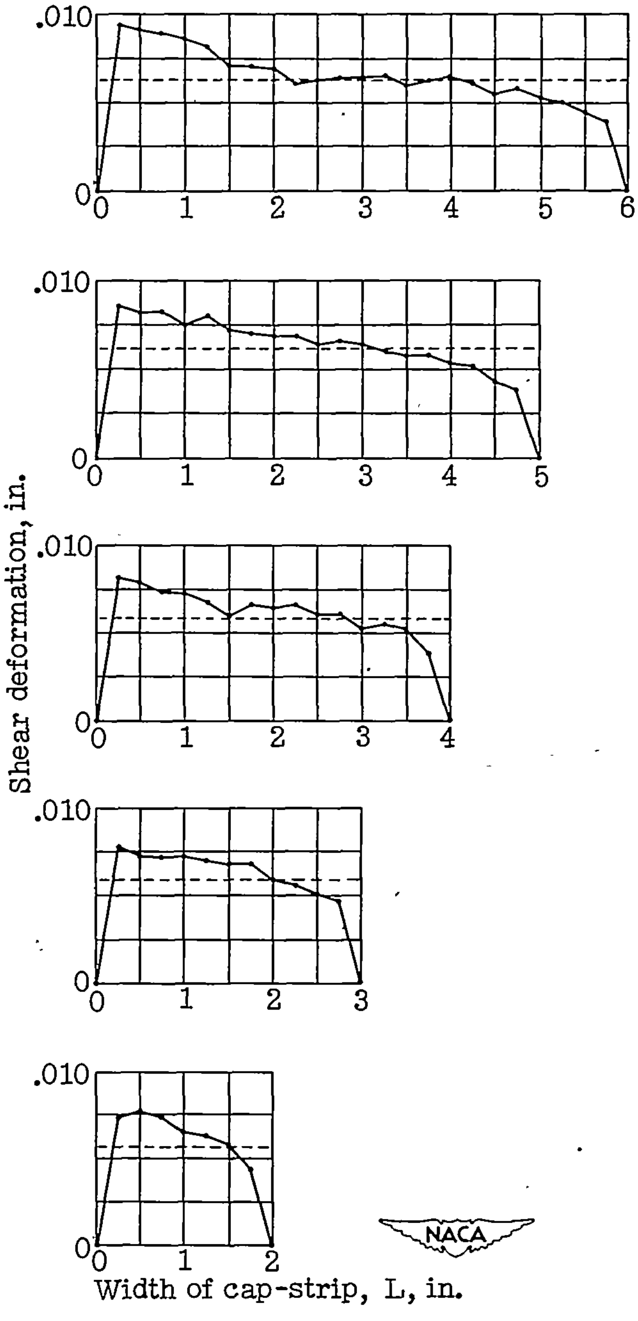
(c) Specimen 6A, left edge.

Figure 3.- Continued.



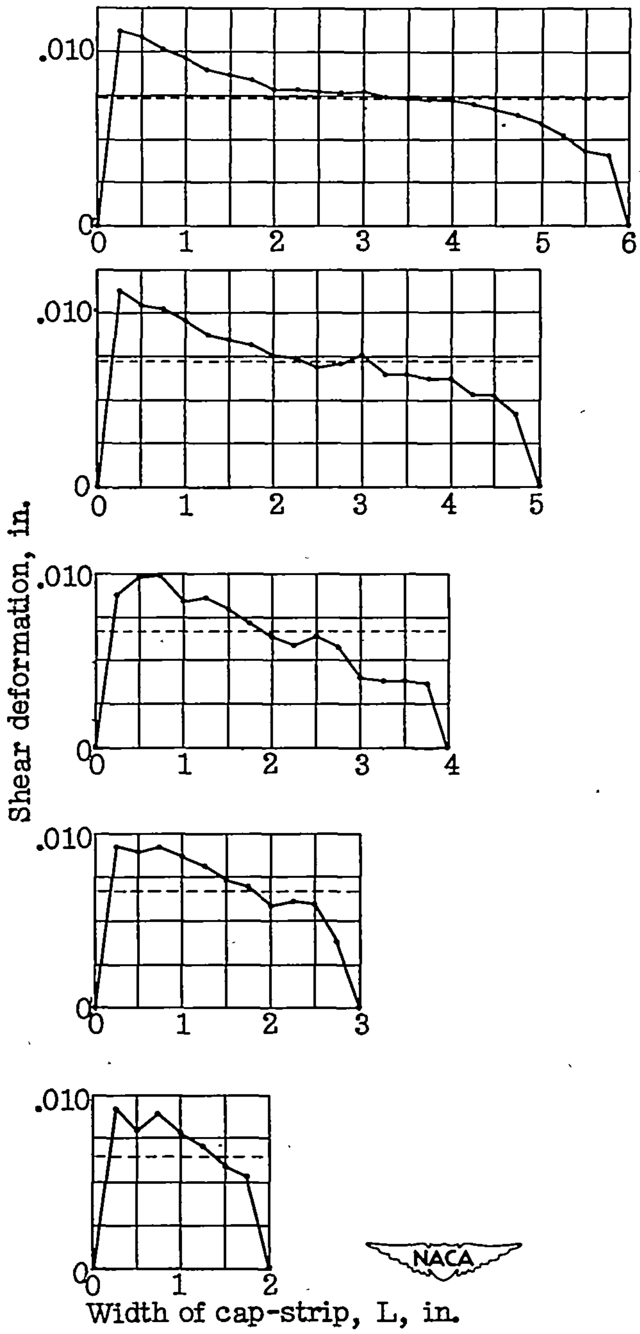
(d) Specimen 6A, right edge.

Figure 3.- Continued.



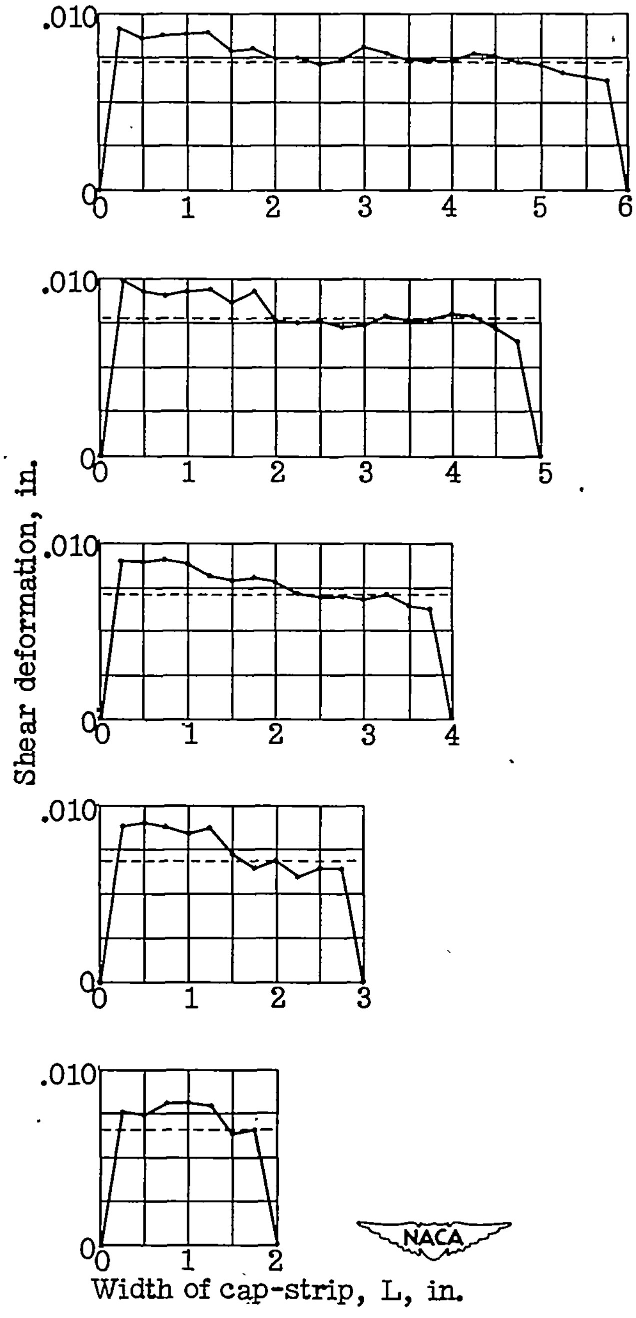
(e) Specimen 8A, left edge.

Figure 3.- Continued.



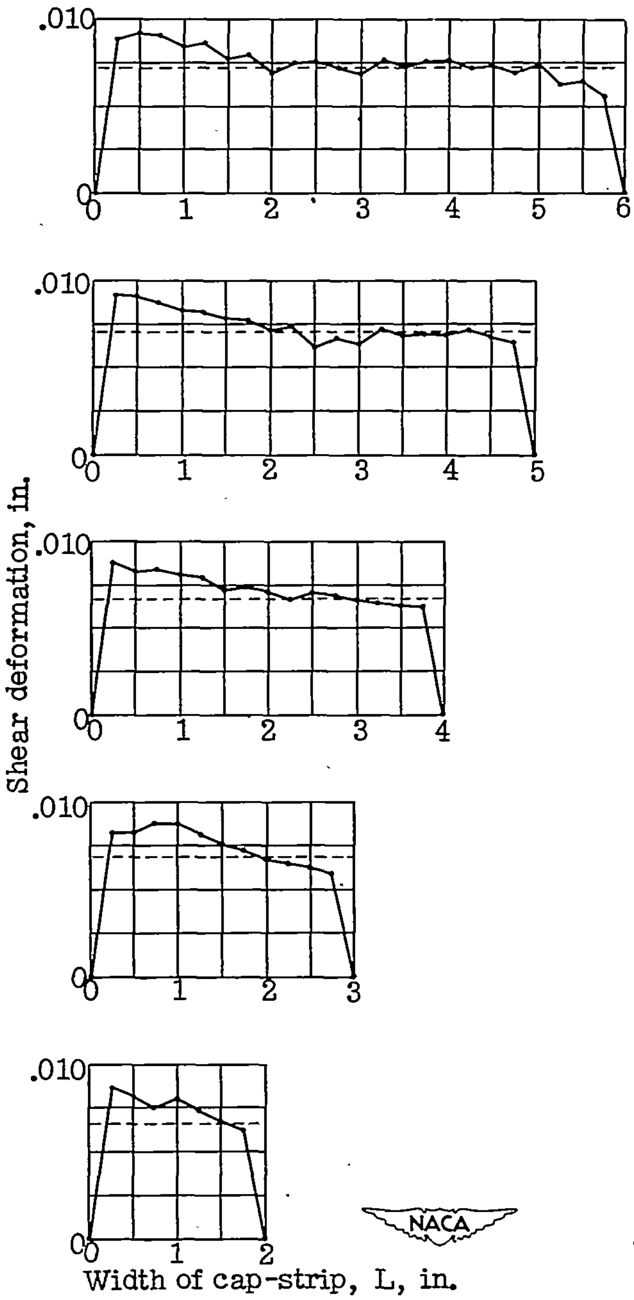
(f) Specimen 8A, right edge.

Figure 3.- Continued.



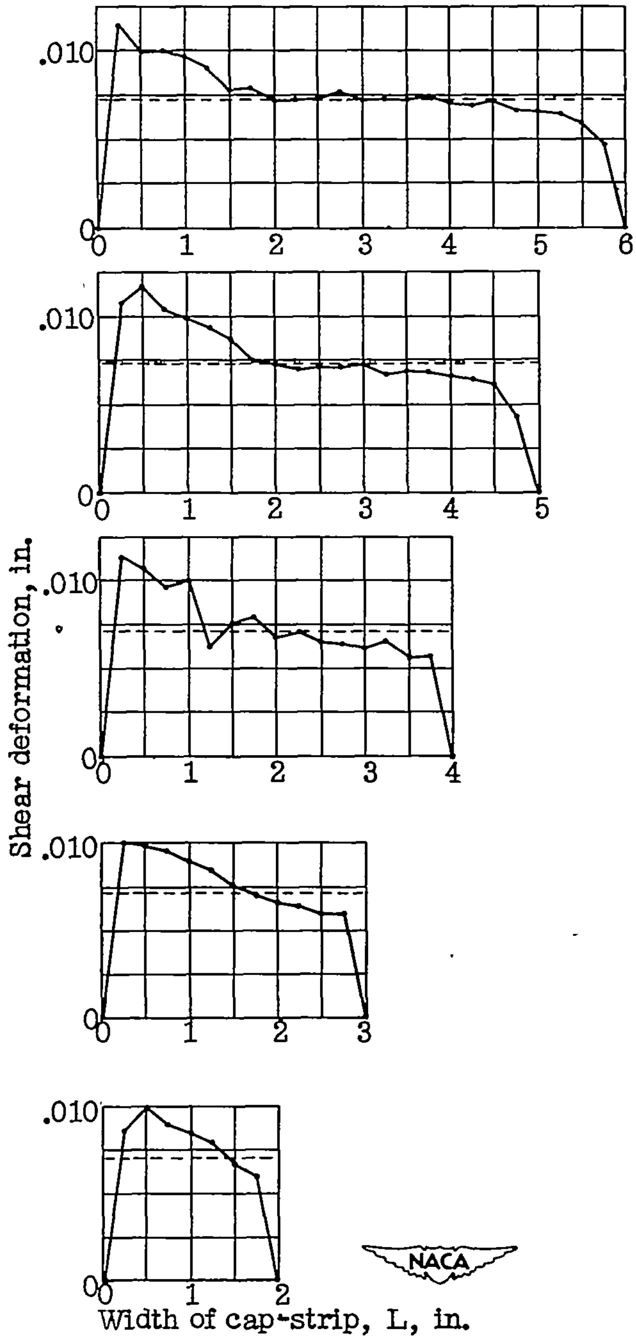
(g) Specimen 9A, left edge.

Figure 3.- Continued.



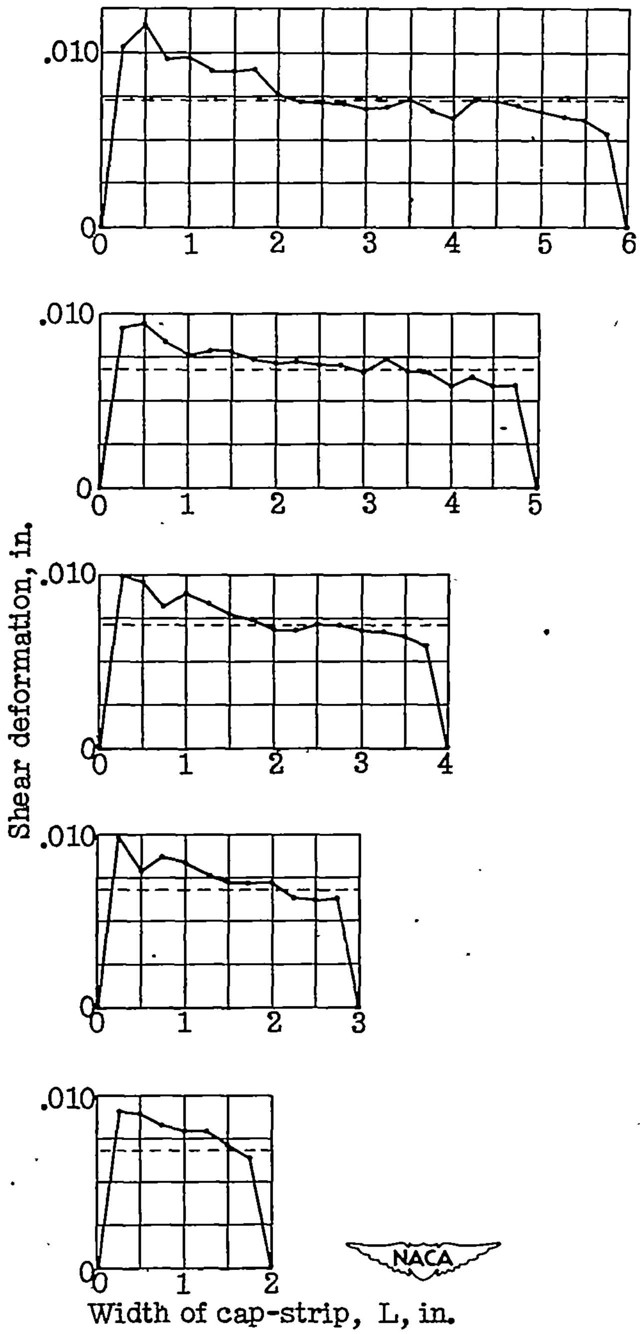
(h) Specimen 9A, right edge.

Figure 3.- Continued.



(i) Specimen 10A, left edge.

Figure 3.- Continued.



(j) Specimen 10A, right edge.

Figure 3.- Concluded.

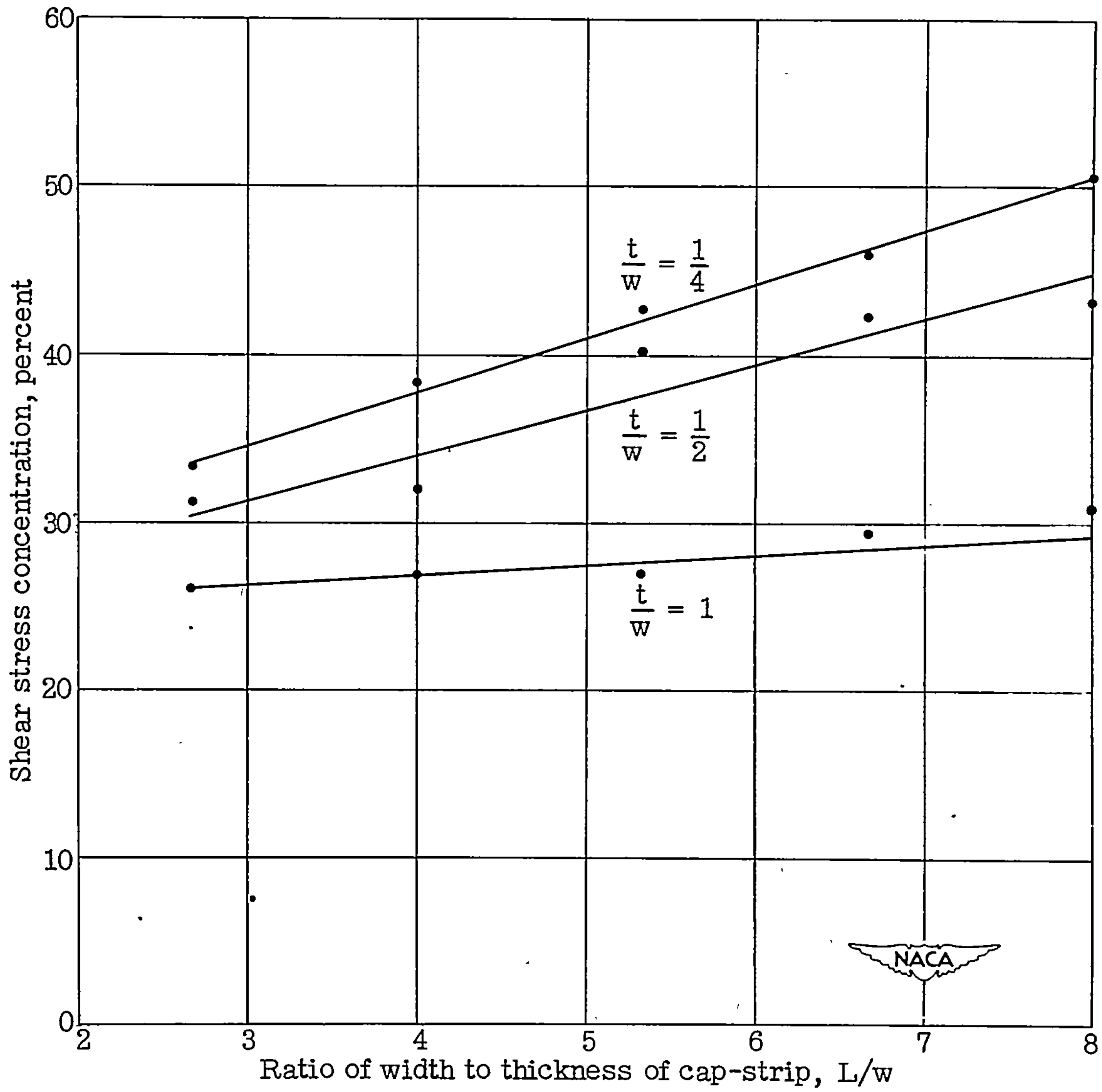


Figure 4.- Effect of width on shear stress concentration in a cap-strip for different ratios of thickness of skin to thickness of cap-strip.

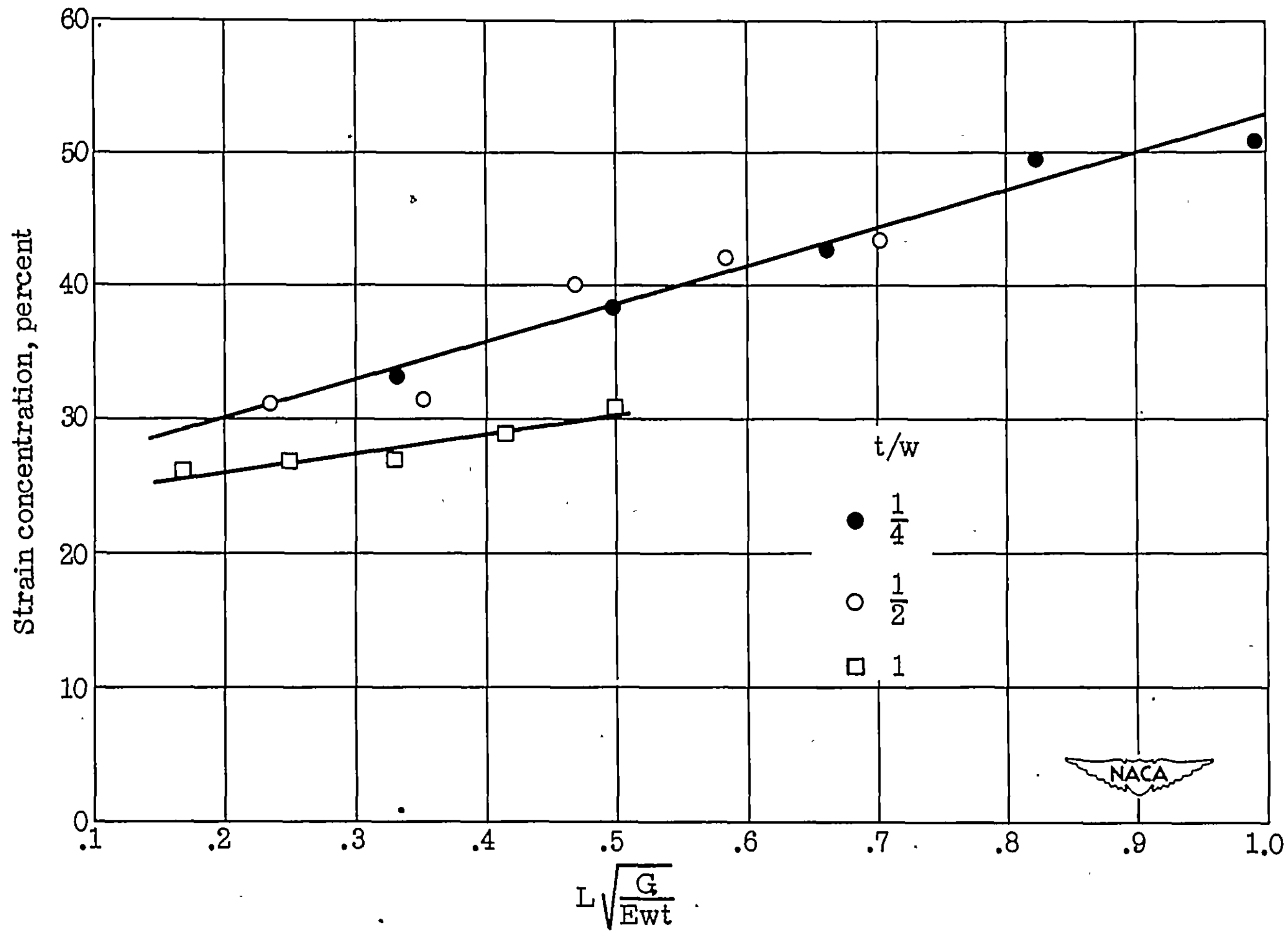


Figure 5.- Strain concentration plotted to parameters suggested by previous investigations.

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